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DILATONIC p -BRANE SOLITONS

H. Lü[†], C.N. Pope[†], E. Sezgin[‡]

Center for Theoretical Physics, Texas A&M University, College Station, Texas 77843

K.S. Stelle^{*}

The Blackett Laboratory, Imperial College, Prince Consort Road, London SW7 2BZ, UK

ABSTRACT

We find new 4-brane and 5-brane solitons in massive gauged $D = 6$, $N = 2$ and $D = 7$, $N = 1$ supergravities. In each case, the solutions preserve half of the original supersymmetry. These solutions make use of the metric and dilaton fields only. We also present more general dilatonic $(D - 2)$ -branes in D dimensions.

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The recent advances in the understanding of duality in string theories have led to a resurgence of interest in supersymmetric p -brane solitons in the supergravities that arise as the low-energy effective actions of fundamental theories of extended objects. These super p -branes may also exist as fundamental objects in their own right. Their importance is based on the speculation that they seem to participate in a web of interconnections in the non-perturbative regime [1]. Further evidence for such connections was recently found in ref. [2] where it was proposed that $D = 11$ supergravity emerges as the strong coupling limit of the $D = 10$ type IIA string. This result suggests that the $D = 11$ supermembrane [3] on S^1 may be equivalent to the $D = 10$ type IIA string if all perturbative and non-perturbative effects are taken into account.

Large classes of super p -brane solutions have been studied in the type IIA, type IIB and heterotic strings, both in 10 dimensions and in lower dimensions (see for example ref. [4]). In general these solutions make use of the antisymmetric tensors and dilaton. In particular, there exists an elementary $(n-2)$ -brane and a solitonic $(D-n-2)$ -brane associated with an n -index antisymmetric tensor field strength in D dimensions. The general solutions of this type were obtained in ref. [5]. A particular case that arises in some supergravity theories is when the theory has a cosmological term of the form $\frac{1}{2}k^2 e^{a\phi}$ in the Lagrangian. This term can be viewed as a special case of the general discussion above, where the field strength is a 0-form. When such a term is present in the Lagrangian, it gives rise to a $(D-2)$ -brane. A recently studied example is the 8-brane [6] in the massive type IIA supergravity in 10 dimensions [7].

In this paper, we shall be concerned with supergravity theories that admit such purely dilatonic p -brane solutions. One class of such theories is that of the gauged supergravity theories (see for example ref. [8]). All of these have a cosmological term, with a coefficient depending on the gauge coupling, corresponding to a potential for the dilaton. Another class of such theories is that admitting an independent potential term associated with a “topological” mass parameter. Some theories admit both types of dilaton potential. In these circumstances, new kinds of $(D-2)$ -brane solution can occur. We shall primarily be concerned for our examples with gauged $D = 7$, $N = 1$ and gauged $D = 6$, $N = 2$ supergravities. The former admits a topological mass term for a 3-index potential; the latter admits a mass term associated with a massive 2-index potential. First let us consider the $D = 7$ theory, whose field content is $(e_M^A, \psi_M^i, B_{MNP}, A_{Mi}^j, \lambda_i, \phi)$, where i is an $SU(2)$ doublet index. The bosonic Lagrangian is given by [9]

$$\begin{aligned}
e^{-1}\mathcal{L} = & R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2 e^{-\frac{8}{\sqrt{10}}\phi} + \sqrt{2}gm e^{-\frac{3}{\sqrt{10}}\phi} + \frac{1}{2}g^2 e^{\frac{2}{\sqrt{10}}\phi} \\
& - \frac{1}{48}e^{-\frac{4}{\sqrt{10}}\phi} F_{MNPQ} F^{MNPQ} - \frac{1}{4}e^{\frac{2}{\sqrt{10}}\phi} F_{MNi}^j F^{MNj}{}^i \\
& + \frac{1}{96}e^{-1}\epsilon^{MNPQRST} F_{MNPQ} F_{RSi}^j A_{Tj}^i + \frac{1}{228}e^{-1}m\epsilon^{MNPQRST} F_{MNPQ} B_{RST} , \tag{1}
\end{aligned}$$

where e is the determinant of the vielbein, m is the topological mass parameter and g is the gauge coupling constant. If m and g are set to zero, the Lagrangian (1) reduces to the standard one for $N = 1$ ungauged supergravity. This would admit standard elementary membrane and solitonic string solutions using the 4-form field strength, and elementary particle and solitonic 3-brane solutions using the 2-form field strengths. Such solutions with the same isotropic ansatz for the metric and antisymmetric tensor no longer occur when the parameters m or g are non-zero. However, as we shall now show, there are new types of solution that describe supersymmetric five branes. These solutions use only the metric and the dilaton, but not the antisymmetric tensors.

The equations of motion for the metric and dilaton, which follow from (1) with the antisymmetric tensors set to zero, are given by

$$\square\phi = S_1, \quad R_{MN} = \frac{1}{2}\partial_M\phi\partial_N\phi + S_2 g_{MN}, \quad (2)$$

where

$$\begin{aligned} S_1 &= -\frac{4m^2}{\sqrt{10}}e^{-\frac{8}{\sqrt{10}}\phi} + \frac{3gm}{\sqrt{5}}e^{-\frac{3}{\sqrt{10}}\phi} - \frac{g^2}{\sqrt{10}}e^{\frac{2}{\sqrt{10}}\phi}, \\ S_2 &= \frac{m^2}{10}e^{-\frac{8}{\sqrt{10}}\phi} - \frac{\sqrt{2}gm}{5}e^{-\frac{3}{\sqrt{10}}\phi} - \frac{g^2}{10}e^{\frac{2}{\sqrt{10}}\phi}. \end{aligned} \quad (3)$$

Note that $S_1 = \frac{\partial}{\partial\phi}S_2$. The metric ansatz is given by

$$ds^2 = e^{2A}dx^\mu dx^\nu \eta_{\mu\nu} + e^{2B}dr^2, \quad (4)$$

where A and B , as well as the dilaton ϕ , are functions of r only. Substituting the metric ansatz into (2), we obtain

$$\begin{aligned} \phi'' + 6A'\phi' - B'\phi' &= e^{2B}S_1, \\ A'' + 6A'^2 - A'B' &= 6A'' - 6A'B' + 6A'^2 + \frac{1}{2}\phi'^2 = e^{2B}S_2, \end{aligned} \quad (5)$$

These equations can be integrated to give rise to two first-order equations, namely

$$\phi' = \frac{4m}{\sqrt{10}}e^{-\frac{4}{\sqrt{10}}\phi+B} - \frac{g}{\sqrt{5}}e^{\frac{1}{\sqrt{10}}\phi+B}, \quad A' = \frac{m}{10}e^{-\frac{4}{\sqrt{10}}\phi+B} + \frac{g}{5\sqrt{2}}e^{\frac{1}{\sqrt{10}}\phi+B}. \quad (6)$$

In fact, as we shall see later, these two first-order equations are implied by requiring that half the supersymmetry be preserved. It is now straightforward to solve the equations. Noting that B can be chosen arbitrarily, by reparametrising r , we can simplify the equations by setting $B = 4A$. We then find that the solution is given by

$$\begin{aligned} B &= 4A, \quad e^{\frac{3}{\sqrt{10}}\phi} = r, \\ e^{-4A} &= \frac{4m}{\sqrt{10}}r^{-\frac{1}{3}} - \frac{g}{\sqrt{5}}r^{\frac{4}{3}}. \end{aligned} \quad (7)$$

Having obtained the bosonic solution, we shall now verify that it preserves half of the original supersymmetry of gauged $N = 1$, $D = 7$ supergravity. The supersymmetry transformation rules for the fermionic fields λ_i and ψ_{Mi} , in a bosonic background in which the antisymmetric tensor fields vanish, are given by [9]

$$\begin{aligned}\delta\lambda_i &= \frac{1}{2\sqrt{2}}\partial_M\phi\Gamma^M\epsilon_i - \frac{m}{\sqrt{5}}e^{-\frac{4}{\sqrt{10}}\phi}\epsilon_i + \frac{g}{2\sqrt{10}}e^{\frac{1}{\sqrt{10}}\phi}\epsilon_i, \\ \delta\psi_{Mi} &= D_M\epsilon_i - \frac{m}{20}e^{-\frac{4}{\sqrt{10}}\phi}\Gamma_M\epsilon_i - \frac{g}{10\sqrt{2}}e^{\frac{1}{\sqrt{10}}\phi}\Gamma_M\epsilon_i.\end{aligned}\quad (8)$$

Thus it follows from (6) that supersymmetry is preserved provided that

$$\epsilon_i = e^{\frac{1}{2}A}\epsilon_i^0, \quad \Gamma_r\epsilon_i^0 = \epsilon_i^0, \quad (9)$$

where ϵ_i^0 is a constant spinor. The 5-brane solution that we have obtained therefore preserves half the supersymmetry. The solution contains two parameters m and g . When $g = 0$, the metric can be expressed as

$$ds^2 = \rho^{\frac{1}{8}}dx^\mu dx^\nu \eta_{\mu\nu} + d\rho^2, \quad (10)$$

and when $m = 0$, the metric can be written as

$$ds^2 = \rho^2 dx^\mu dx^\nu \eta_{\mu\nu} + d\rho^2, \quad (11)$$

where $\rho \propto r^{\frac{4}{3}}$ for the first case and $\rho \propto r^{-\frac{1}{3}}$ for the second case.

Now we turn to gauged $D = 6$, $N = 2$ supergravity. The field content is $(e_M^A, \psi_M^i, B_{MN}, B_M, A_M^{ij}, \lambda_i, \phi)$, where i is a $USp(4)$ vector index. The bosonic Lagrangian is given by [10]

$$\begin{aligned}e^{-1}\mathcal{L} &= R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2 e^{-\frac{3}{\sqrt{2}}\phi} + 2gm e^{-\frac{1}{\sqrt{2}}\phi} + \frac{1}{2}g^2 e^{\frac{1}{\sqrt{2}}\phi} \\ &\quad - \frac{1}{12}e^{\sqrt{2}\phi}G_{MNP}G^{MNP} - \frac{1}{4}e^{-\frac{1}{\sqrt{2}}\phi}(H_{MN}H^{MN} + F_{MN}^{ij}F_{MNij}) \\ &\quad - \frac{1}{16}e^{-1}\epsilon^{MNPQRS}(G_{MN}G_{PQ} + mB_{MN}G_{PQ} + \frac{1}{3}m^2B_{MN}B_{PQ} + F_{MN}^{ij}F_{PQij})B_{RS},\end{aligned}\quad (12)$$

where $G_{MNP} = 3\partial_{[M}B_{NP]}$, $G_{MN} = 2\partial_{[M}B_{N]}$ and $H_{MN} = G_{MN} + mB_{MN}$. The relevant terms in the supersymmetry transformation rules for the fermionic fields are given by [10]

$$\begin{aligned}\delta\lambda_i &= \frac{1}{2\sqrt{2}}\Gamma^M\partial_M\phi\epsilon + \frac{1}{4\sqrt{2}}(ge^{\frac{1}{2\sqrt{2}}\phi} - 3me^{-\frac{3}{2\sqrt{2}}\phi})\Gamma_7\epsilon_i, \\ \delta\psi_{Mi} &= D_M\epsilon_i - \frac{1}{8\sqrt{2}}(ge^{\frac{1}{2\sqrt{2}}\phi} + me^{-\frac{3}{2\sqrt{2}}\phi})\Gamma_M\Gamma_7\epsilon_i.\end{aligned}\quad (13)$$

Proceeding as in the case of $D = 7$, we obtain the 4-brane solution, given by

$$\begin{aligned}B &= 3A, \quad e^{\frac{1}{\sqrt{2}}\phi} = r, \\ e^{-3A} &= \frac{3m}{2\sqrt{2}}r^{-\frac{1}{2}} - \frac{g}{2\sqrt{2}}r^{\frac{3}{2}}.\end{aligned}\quad (14)$$

It is easy to verify that this solution preserves half of the original $D = 6$, $N = 2$ supersymmetry, with ϵ_i satisfying

$$\epsilon_i = e^{\frac{1}{2}A} \epsilon_i^0, \quad \Gamma_r \Gamma_7 \epsilon_i^0 = \epsilon_i^0. \quad (15)$$

When m or g is zero, the metrics of the 4-brane solutions can be simplified, and are given by

$$\begin{aligned} ds^2 &= \rho^{\frac{2}{9}} dx^\mu dx^\nu \eta_{\mu\nu} + d\rho^2, & g = 0, \\ ds^2 &= \rho^2 dx^\mu dx^\nu \eta_{\mu\nu} + d\rho^2, & m = 0, \end{aligned} \quad (16)$$

where $\rho \propto r^{\frac{9}{4}}$ for the first case and $\rho \propto r^{-\frac{1}{4}}$ for the second.

Having obtained new 5-brane and 4-brane solutions in $D = 7$, $N = 1$ and $D = 6$, $N = 2$ gauged supergravities respectively, it is interesting to examine the relation of the two solutions. Since $D = 6$, $N = 2$ gauged supergravity cannot be obtained from Kaluza-Klein dimensional reduction of $D = 7$, $N = 1$ supergravity, the 4-brane solutions in $D = 6$ with two parameters m and g are in general not related to the 5-brane solutions by dimensional reduction. However when $m = 0$, the two metrics of the 5-brane and 4-brane solutions can be related by dimensional reduction. To see this, we note that whenever one dimensionally reduces a term of the form $e^{-a\phi} F_n^2$ in a Kaluza-Klein theory (our case corresponds to $n = 0$, *i.e.* a 0-form field strength), the value of Δ , defined by $a^2 = \Delta - 2(n-1)(D-n-1)/(D-2)$, is always preserved [5]. The Δ value for the pure g potential is -2 for both $D = 7$ and $D = 6$ whilst the Δ value for the pure m potential is 4 for $D = 7$ and 2 for $D = 6$. Thus the above metrics for $m = 0$ could be related by dimensional reduction, while the metrics for $m \neq 0$ can not. Similarly, the 5-brane metric with $\Delta = 4$ in $D = 7$ could be related to the 8-brane metric in $D = 10$ [6] by dimensional reduction. The details of dimensional reduction between supergravity theories with dilaton potentials of the types considered in this paper have not yet been worked out, however.

Now we shall generalise these results and discuss the $(D-2)$ -branes in D dimensional supergravity. In general, there are two different types of $(D-2)$ -brane solutions. One of them is obtained by making use of a cosmological constant term *i.e.* as we discussed previously. In some cases, the cosmological constant term can be described in terms of a D -form field strength. Under these circumstances, one can make use of this field strength to construct an elementary $(D-2)$ -brane solution. In fact the former description with the cosmological term can be viewed as a solitonic solution using a 0-form field strength. (However, note that in the formulation using a cosmological term, the $(D-2)$ -brane is necessarily present, since Minkowski spacetime is not a solution of the equations of motion.) The metrics of these two types of $(D-2)$ branes are identical, and hence without loss of generality, we can focus only on the $(D-2)$ -branes of the first type. Unlike the case of gauged $D = 7$, $N = 1$ and $D = 6$, $N = 2$ supergravity, in general the supergravity theo-

ries constructed so far admit no more than one cosmological term. The bosonic Lagrangian of D dimensional supergravity involving the metric, the dilaton and a cosmological term is given by

$$e^{-1}\mathcal{L} = R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2 e^{-a\phi} , \quad (17)$$

where a can be parametrised as $a^2 = \Delta + \frac{2(D-1)}{D-2}$, and the value of Δ depends on the specific supergravity theory. It is a simple matter to solve the field equations with the isotropic metric ansatz (4). In fact the solution is a special case of the general results obtained for an n -form field strength in ref. [5], in which we take $n = 0$. The metric of the $(D-2)$ -brane solution is given by [5]

$$ds^2 = r^{\frac{4}{\Delta(D-2)}} dx^\mu dx^\nu \eta_{\mu\nu} + r^{\frac{4(D-1)}{\Delta(D-2)}} dr^2 . \quad (18)$$

which can be re-expressed as

$$ds^2 = \rho^{\frac{4}{2(D-1)+\Delta(D-2)}} dx^\mu dx^\nu \eta_{\mu\nu} + d\rho^2 , \quad (19)$$

where $\rho \propto r^{\frac{2(D-1)}{\Delta(D-2)}+1}$. We expect that such a solution preserves half of the supersymmetry. An exception arises when the dilaton is absent, which corresponds to $\Delta = -2(D-1)/(D-2)$. In such a case the metric of the solution becomes $ds^2 = e^\rho dx^\mu dx^\nu \eta_{\mu\nu} + d\rho^2$, which is anti-de Sitter space, and hence all of the supersymmetry is preserved. It is easy to see that the metric (19) gives rise precisely to the metrics (10), (11) and (16) when $D = 7$ with $\Delta = 4$ and $\Delta = -2$ and $D = 6$ with $\Delta = 2$ and $\Delta = -2$ respectively. Other examples include the ($\Delta = 4$) 8-brane solution of the massive type IIA supergravity in 10 dimensions [6]. An example in which all the supersymmetry is preserved is provided by the “supermembrane” in $D = 4$, $N = 1$ supergravity with a cosmological term, where there is no dilaton field.

Although only two supergravity theories constructed so far contain both the mass and gauge parameters m and g , it is nevertheless of interest to obtain solutions in a generic dimension for a bosonic theory with the two parameters. If further supergravity theories with the two parameters exist, then the results obtained below would be applicable. The relevant part of the Lagrangian for such a theory is

$$e^{-1}\mathcal{L} = R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2 e^{-a_1\phi} + \frac{1}{2}g^2 e^{a_2\phi} + \lambda g m e^{\frac{a_2-a_1}{2}\phi} . \quad (20)$$

The equations of motion with the metric ansatz (4) are given by

$$\begin{aligned} \phi'' + (dA' - B')\phi' &= S_1 , \\ A'' + (dA' - B')A' &= dA'' + d(A' - B')A' + \frac{1}{2}\phi'^2 = S_2 , \end{aligned} \quad (21)$$

where

$$\begin{aligned} S_1 &= -\frac{1}{2}a_1 m^2 e^{-a_1 \phi + 2B} - \frac{1}{2}a_2 g^2 e^{a_2 \phi + 2B} - \frac{1}{2}(a_2 - a_1) \lambda g m e^{\frac{1}{2}(a_2 - a_1) \phi + 2B} , \\ S_2 &= \frac{1}{2(D-2)} (m^2 e^{-a_1 \phi} - g^2 e^{a_2 \phi} - \lambda g m e^{\frac{1}{2}(a_2 - a_1) \phi}) e^{2B} . \end{aligned} \quad (22)$$

In order to solve the equations, we make a supersymmetry-inspired ansatz, namely

$$\begin{aligned} \phi' &= x_1 e^{-\frac{1}{2}a_1 \phi + B} + x_2 e^{\frac{1}{2}a_2 \phi + B} , \\ A' &= y_1 e^{-\frac{1}{2}a_1 \phi + B} + y_2 e^{\frac{1}{2}a_2 \phi + B} , \\ S_1 &= \alpha \phi'^2 + \beta \phi' A' . \end{aligned} \quad (23)$$

Substituting this ansatz into the equations of motion (21), we find that we can solve for $x_1, x_2, y_1, y_2, \alpha$ and β in terms of the parameters a_1, a_2, g, m and λ . The expressions are very complicated, and we shall not present them here. However we note that there are two distinct solutions. The constants x_1, x_2, y_1 and y_2 take different values in the two solutions, but β and α are the same for each solution. In particular, the value of α is simple, given by $\alpha = \frac{1}{2}(a_2 - a_1)$. Choosing $B = (d - \beta)A$, we find that the solutions for the $(D - 2)$ -brane take the form

$$\begin{aligned} B &= (d - \beta)A , \quad e^{\frac{1}{2}(a_1 - a_2)\phi} = r , \\ e^{-(d - \beta)A} &= x_1 r^{\frac{a_2}{a_2 - a_1}} + x_2 r^{-\frac{a_1}{a_2 - a_1}} . \end{aligned} \quad (24)$$

The two solutions differ only in the values of x_1 and x_2 . In the cases $D = 7$ and $D = 6$, one of the above solutions includes the supersymmetric 4-brane and 5-brane that we obtained previously. The other corresponds to non-supersymmetric 4-brane and 5-brane solutions.

In concluding, we would like to make some comments on the asymptotic structure of the solutions (7,14). $(D - 2)$ -brane solutions in D dimensions have only one transverse dimension, and so the usual discussion of whether a BPS bound written in terms of an integrated charge is saturated becomes somewhat awkward. Let us first consider the question of asymptotic flatness in the transverse direction. For the $D = 7$ solution (7), obtained from our metric ansatz (4) with $B = 4A$, we may write the curvature 2-form Θ^{MN} in terms of basis 1-forms ($e^\mu = e^A dx^\mu, e^z = e^{4A} dr$), finding

$$\begin{aligned} \Theta^{z\mu} &= (-A'' + 3(A')^2) e^{-8A} e^z \wedge e^\mu , \\ \Theta^{\mu\nu} &= -(A')^2 e^{-8A} e^\mu \wedge e^\nu . \end{aligned} \quad (25)$$

For the $D = 6$ solution (14), with $B = 3A$, in terms of the basis one-forms ($e^\mu = e^A dx^\mu, e^z = e^{3A} dr$) one finds

$$\begin{aligned} \Theta^{z\mu} &= (-A'' + 2(A')^2) e^{-6A} e^z \wedge e^\mu , \\ \Theta^{\mu\nu} &= -(A')^2 e^{-6A} e^\mu \wedge e^\nu . \end{aligned} \quad (26)$$

In order to find the flat regions, we need to discuss the cases $g = 0$ and $g \neq 0$ separately. When $g = 0$, the curvature for solution (7) falls off as $r \rightarrow \infty$ like $r^{-8/3}$ in the 1-form basis and like r^{-3} for (14). Thus, the $r \rightarrow \infty$ region is asymptotically flat. In all cases discussed in this paper, the dilaton is proportional to $\log r$. Whether this means that the flat space at transverse infinity is “empty” or not is open to debate. The failure of the dilaton to fall off is a direct consequence of the low codimension of the solution.

Now consider the case $g \neq 0$. In this case, the expressions (25,26) give a rising curvature as $r \rightarrow \infty$, growing (in the chosen 1-form bases) like $r^{2/3}$ for (7) and like r for (14). Thus, the $r \rightarrow \infty$ region is not asymptotically flat for this case. However, the region where $r \rightarrow 0$ is asymptotically flat in this case provided $m = 0$. In both the $g = 0$ and $m = 0$ cases, the proper distance along transverse geodesics between $r = 0$ and $r = \infty$ diverges. Thus it emerges that provided *either* $g = 0$ *or* $m = 0$, there is a flat region that may be considered to be transverse infinity. In the $m = 0$ case, a further coordinate transformation $r \rightarrow 1/r$ relabels transverse infinity in the standard fashion. Note that this flip does not destroy the proportionality between the dilaton and $\log r$.

We shall not proceed further here with a standard analysis of the BPS bound. However, the saturation of this bound should be guaranteed by the preservation of part of the original supersymmetry, as we showed in Eqs (9,15). The question of finding “normalizable” zero-modes describing the fluctuations about our BPS solutions is again somewhat awkward here, without a convenient definition of the charges that would normally be required to be convergent transverse integrals in higher codimension cases. Nonetheless, one may identify appropriate worldvolume supermultiplets that the zero modes could belong to. For the $D = 7$ solution (7), the worldvolume is $d = 6$ dimensional, and there is a natural $d = 6$ supermultiplet [11] $(A_{\mu\nu}^+, \lambda_{\alpha i}, \varphi)$, where the 2-form potential $A_{\mu\nu}^+$ has a self-dual 3-form field strength $F_{\mu\nu\rho}^+$. The dimensional reduction of this multiplet to $d = 5$ is correspondingly available for the zero modes of the $D = 6$ solution (14). Consequently, we may tentatively identify these multiplets as the zero-mode supermultiplets.

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